

# The Cosmic Dipole Tension

View with the SKA

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Sydney Institute for Astronomy  
The University of Sydney

*Supervised by*  
Geraint Lewis  
Tara Murphy

February 10, 2026



THE UNIVERSITY OF  
**SYDNEY**

Asian-Pacific SKA  
Science Meeting

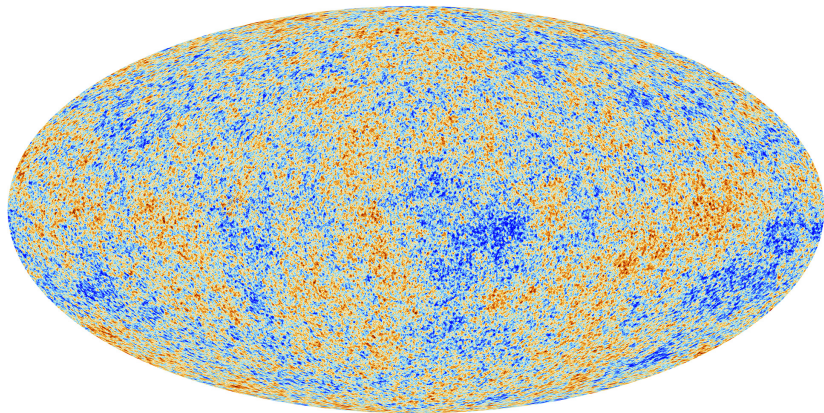
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February 2026



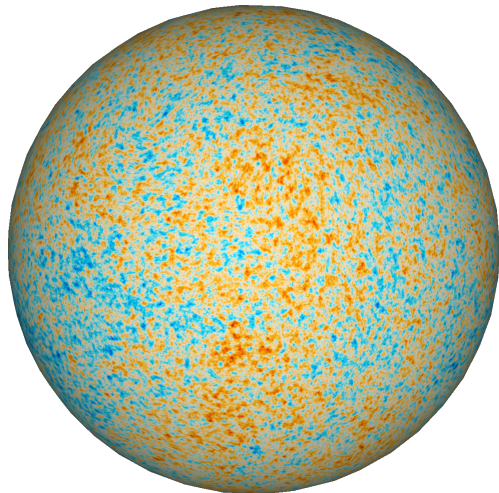
- The cosmological principle might be in trouble.
- SKA will offer new insight.
- How can we get ready?

# The Kinematic Dipole



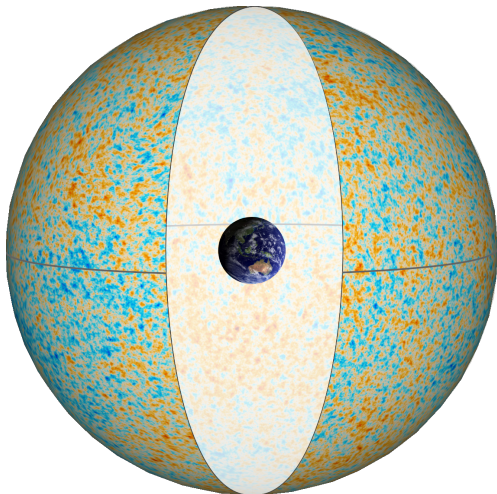
CMB temperature map (Planck satellite).

# The Kinematic Dipole



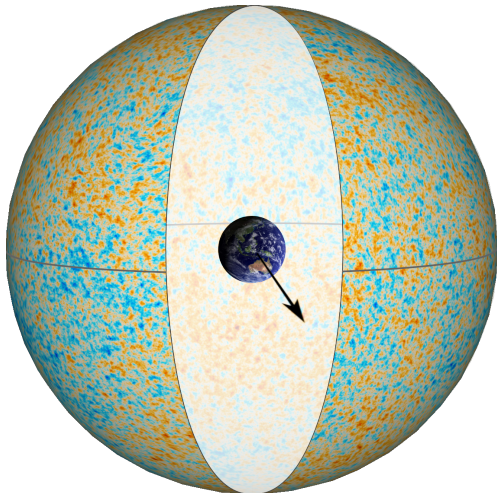
CMB as a sphere.

# The Kinematic Dipole



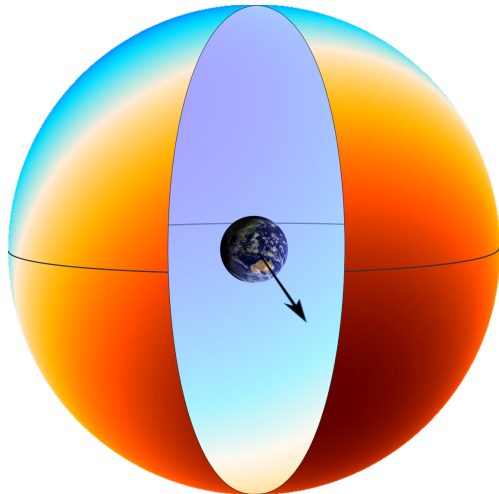
CMB as a sphere (Earth inside).

# The Kinematic Dipole



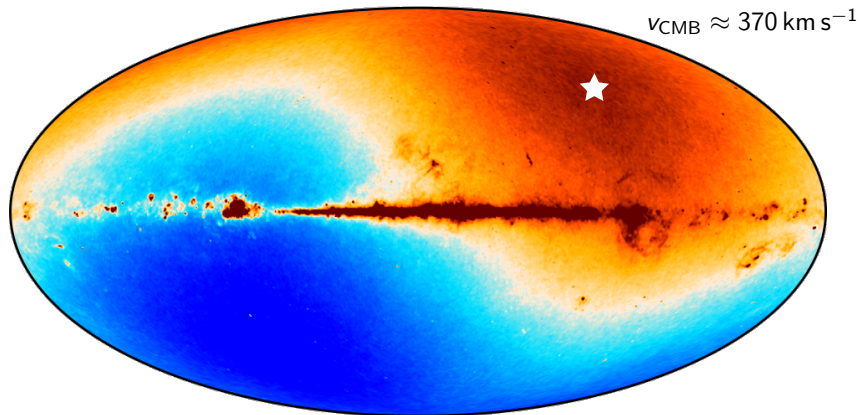
We're moving through the Universe!

# The Kinematic Dipole



CMB dipole as sphere (Earth inside).

# The Kinematic Dipole



CMB temperature map (dipole included; BeyondPlanck).

★: dipole direction.

# The Cosmic Dipole — Ellis & Baldwin (1984)

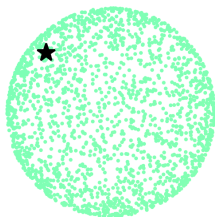
Special relativity:      ➤ Aberration      ➤ Doppler boosting

# The Cosmic Dipole — Ellis & Baldwin (1984)

Special relativity:

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➤ Doppler boosting



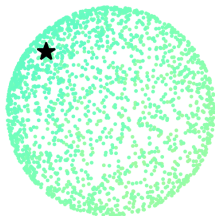
Speed (c)  0.025

# The Cosmic Dipole — Ellis & Baldwin (1984)

Special relativity:

➤ Aberration

➤ Doppler boosting



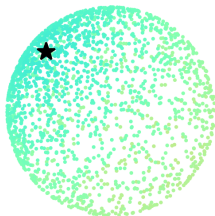
Speed (c)  0.244

# The Cosmic Dipole — Ellis & Baldwin (1984)

Special relativity:

➤ Aberration

➤ Doppler boosting



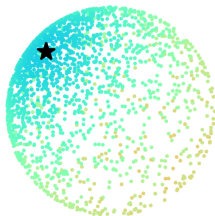
Speed (c)  0.462

# The Cosmic Dipole — Ellis & Baldwin (1984)

Special relativity:

➤ Aberration

➤ Doppler boosting



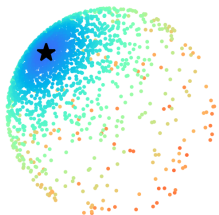
Speed (c)  0.681

# The Cosmic Dipole — Ellis & Baldwin (1984)

Special relativity:

➤ Aberration

➤ Doppler boosting



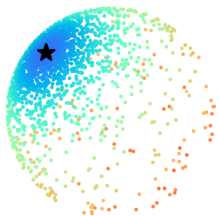
Speed (c)  0.9

# The Cosmic Dipole — Ellis & Baldwin (1984)

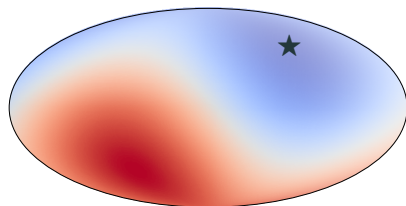
Special relativity:


➤ Aberration

➤ Doppler boosting



Speed (c)  0.9



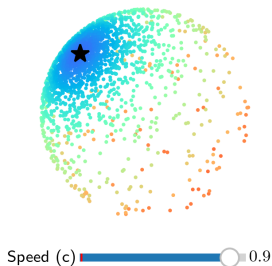
  
Redshift Blueshift

# The Cosmic Dipole — Ellis & Baldwin (1984)

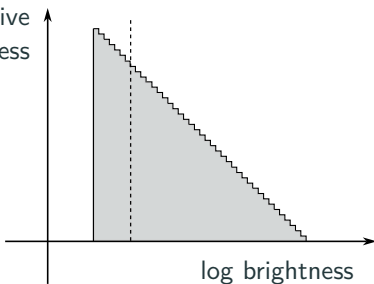
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Cumulative  
brightness

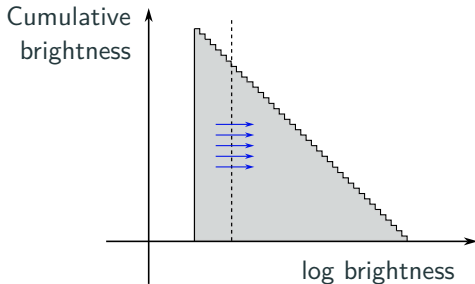
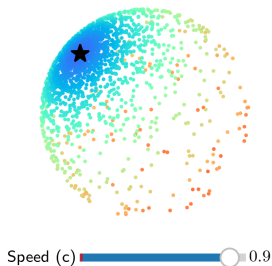


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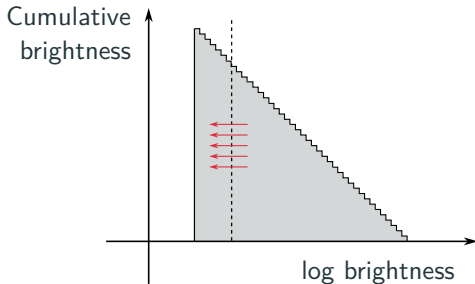
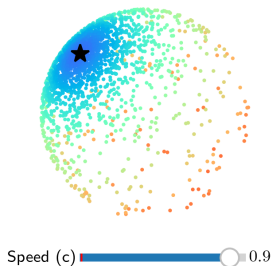


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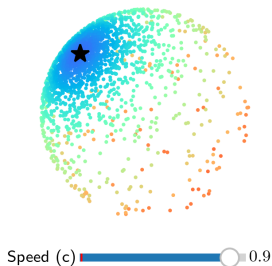


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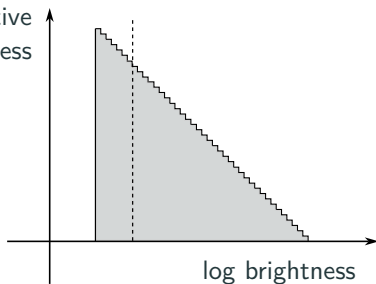
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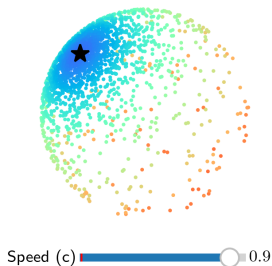


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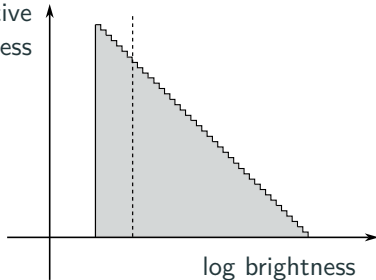
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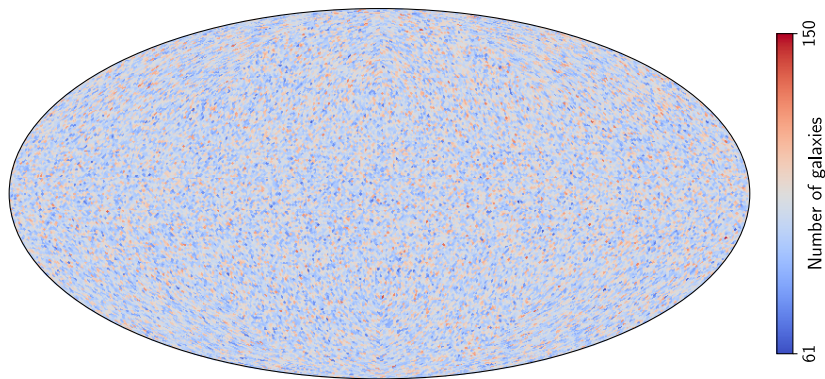


$$D_{\text{CMB}} = [2 + x(1 + \alpha)] \frac{v_{\text{CMB}}}{c}$$

Typical values:  $\approx 0.5\%$

# Counting Galaxies

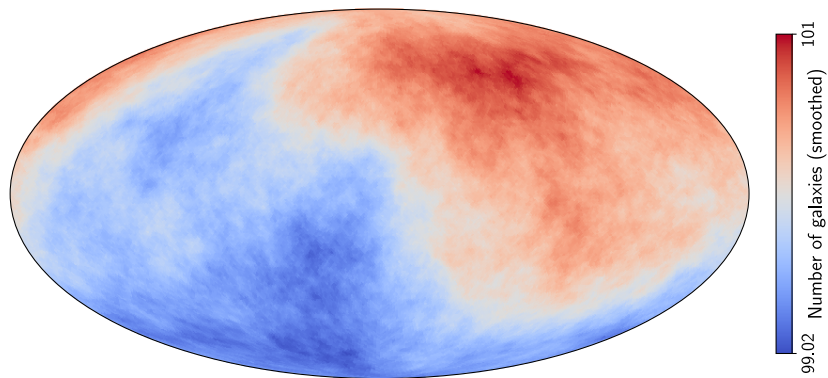
$$N_i = \bar{N}(1 + \mathcal{D} \cos \theta_i)$$



Simulated isotropic galaxy map (+ dipole).

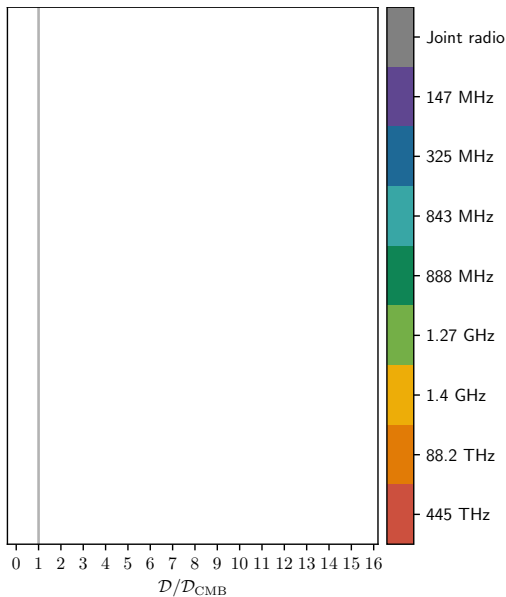
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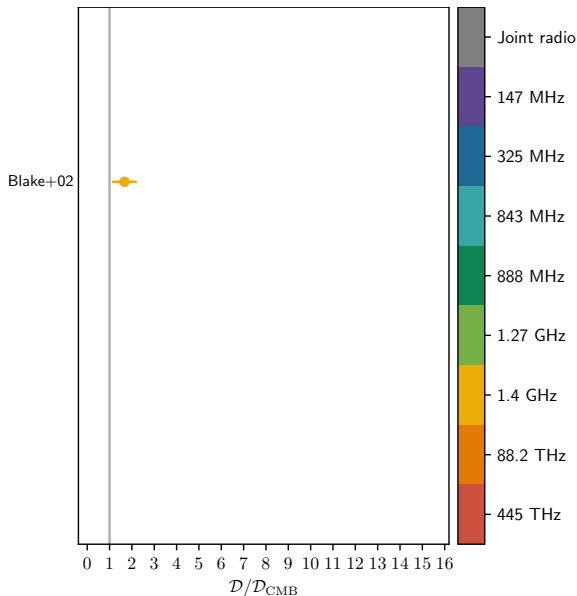
Simulated isotropic galaxy map (+ dipole).

# The Amplitude Excess



*Cosmic dipole  
should be  
consistent with  
CMB dipole...*

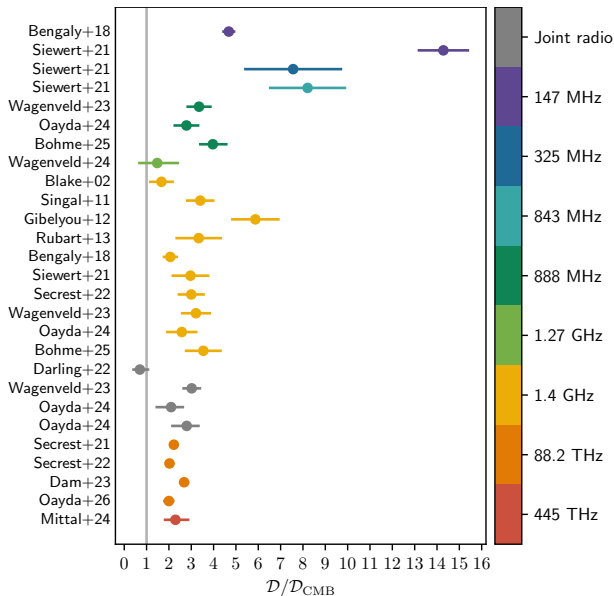
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*All is well!*

# The Amplitude Excess

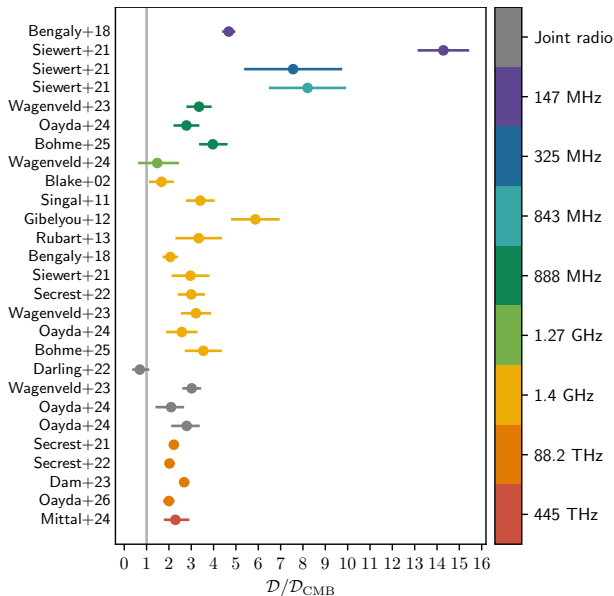


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*All is well!*

*Wait...*

# The Amplitude Excess



*Cosmic dipole  
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CMB dipole...*



*All is well!*

*Wait...*

**700–1100 km/s**

**The cosmic dipole tension is a serious issue for  $\Lambda$ CDM.**

## The cosmic dipole in the Quiaia sample of quasars: a Bayesian analysis

Vasudev Mittal <sup>1</sup>★, Oliver T. Oayda<sup>2</sup>★† and Geraint F. Lewis <sup>2</sup>

<sup>1</sup>*Department of Physical Sciences, IISER Mohali, Knowledge City, Sector 81, SAS Nagar, Manauli PO 140306, Punjab, India*



<sup>2</sup>*Sydney Institute for Astronomy, School of Physics A28, The University of Sydney, NSW 2006, Australia,*

Quiaia sample, *Gaia* DR3 quasars

Storey-Fisher et al. (2024)

# Optical Quasars — A Dusty Death?

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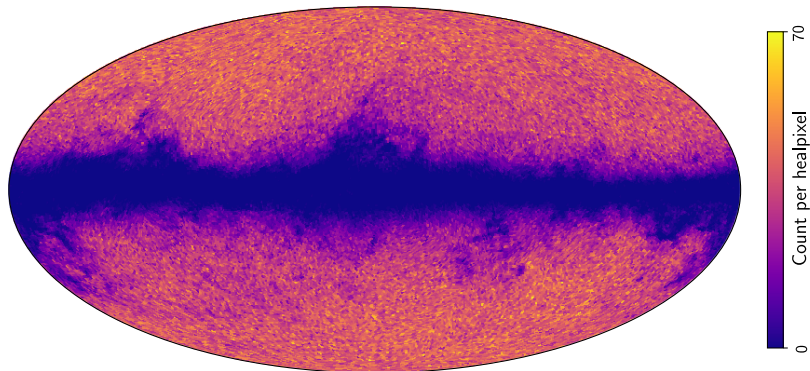
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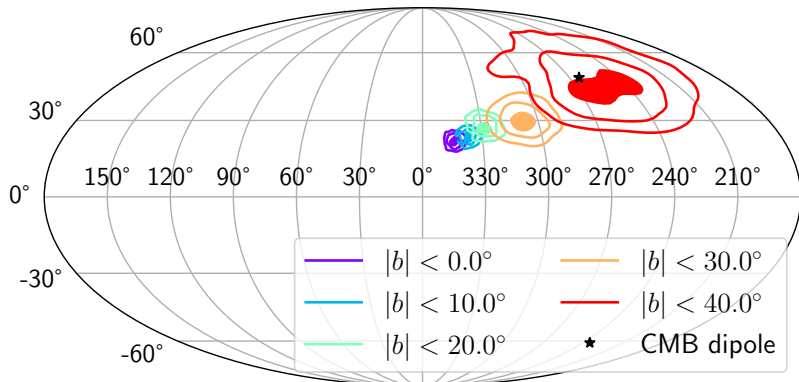
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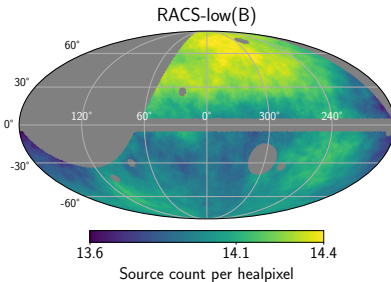
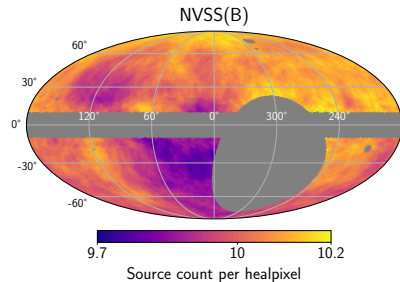
Amplitude  $\mathcal{D}$  ( $10^{-3}$ )     $37^{+4}_{-4}$      $34^{+4}_{-4}$      $25^{+5}_{-5}$      $17^{+6}_{-6}$      $11^{+6}_{-5}$     5★

## A Bayesian approach to the cosmic dipole in radio galaxy surveys: joint analysis of NVSS & RACS






Oliver T. Oayda <sup>1</sup>★, Vasudev Mittal <sup>1,2</sup>, Geraint F. Lewis <sup>1</sup> and Tara Murphy <sup>1</sup>

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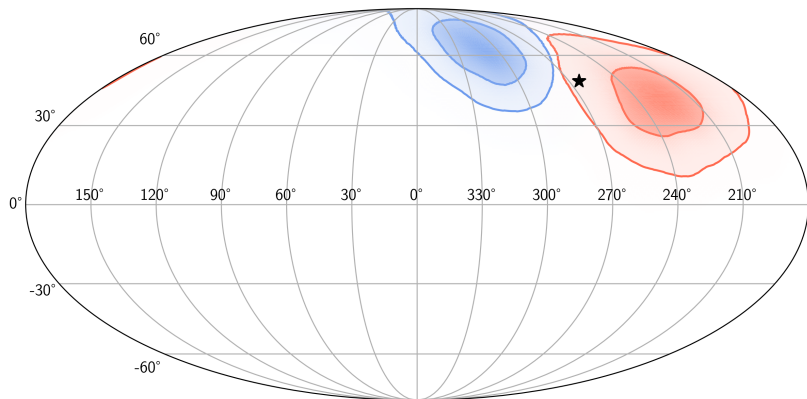


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NVSS and RACS-low1 dipole with CMB dipole direction (★).

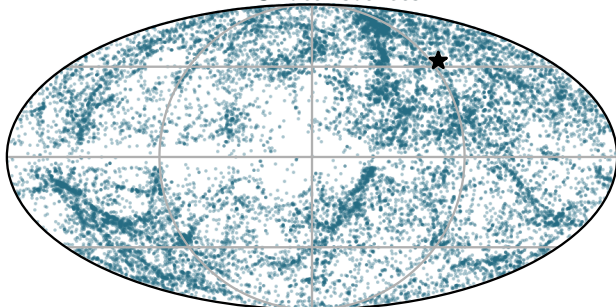
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2MRS local sources



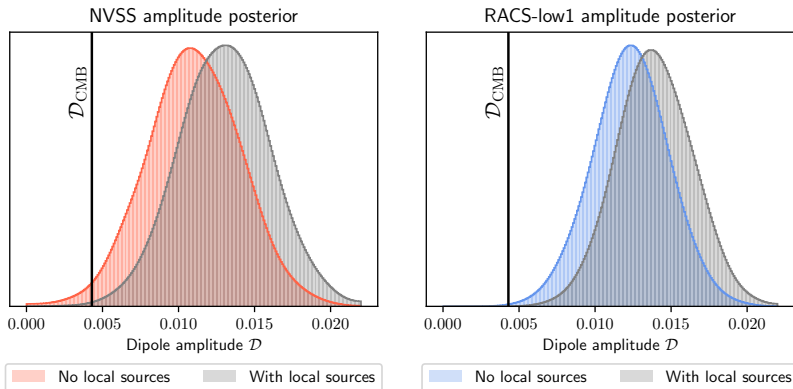
Cross-matching up to  $z \approx 0.04 \implies 10\text{--}15\%$  drop in  $\mathcal{D}$

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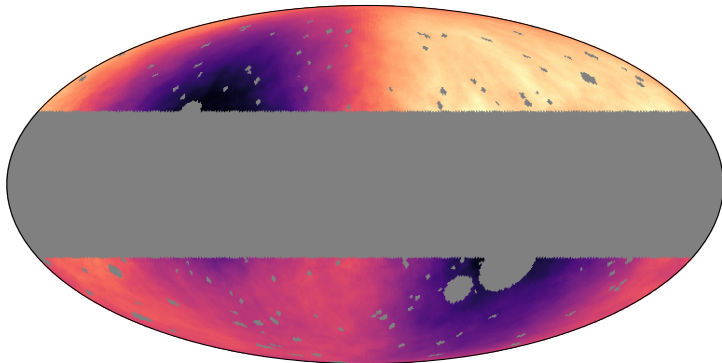
## A Test of the Cosmological Principle with Quasars

Nathan J. Secrest<sup>1</sup> , Sebastian von Hausegger<sup>2,3,4</sup> , Mohamed Rameez<sup>5</sup> , Roya Mohayaee<sup>3</sup> , Subir Sarkar<sup>4</sup> , and Jacques Colin<sup>3</sup> 









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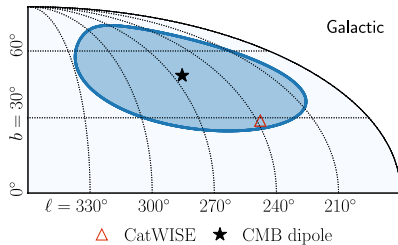
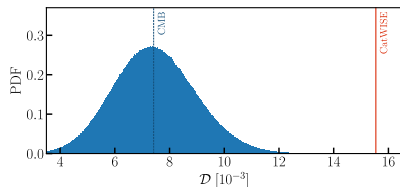
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Null significance test (dipole amplitude + direction).

## Wising up to CatWISE: using simulation-based inference to interpret the ecliptic bias and confirm the cosmic dipole excess

Oliver T. Oyda<sup>1\*</sup> and Geraint F. Lewis<sup>2</sup>

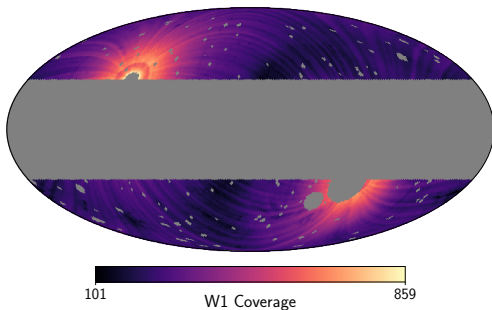
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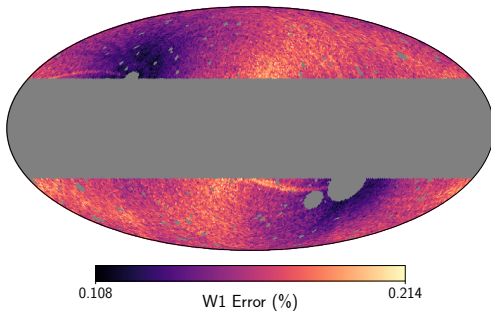
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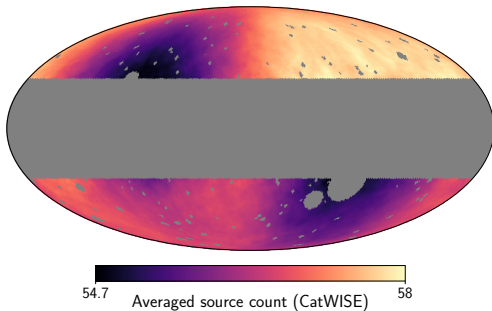
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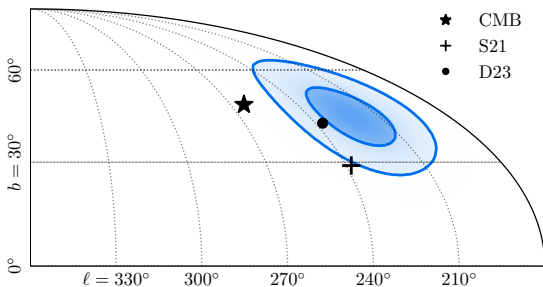
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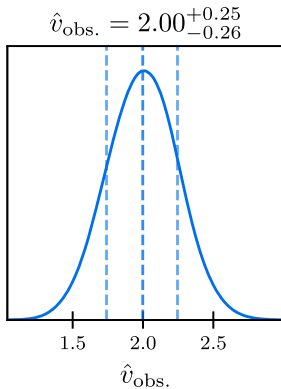
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➤ SBI-based approach confirms  $\times 2$  excess



**What will SKA make of all this?**

# Future with the SKA

- Premier sensitivity and depth
- Large-scale coverage of the southern sky
- Radio  $\Rightarrow$  mitigate dust absorption
- **Simulate** an SKA sky

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## The Cosmic Radio Dipole and Observer Effects in SKA all-sky surveys

D. Bertacca,<sup>1,2,3</sup> L. Böhme,<sup>4</sup> B. Bottazzi Baldi,<sup>1,2</sup> C. Burigana,<sup>5,6</sup> M. Y. Elkhatab,<sup>7,8,9,10</sup> C. L. Hale,<sup>11,12</sup> S. von Hausegger,<sup>13</sup> H.-R. Klöckner,<sup>14</sup> M. Land-Strykowski,<sup>15</sup> G. Lewis,<sup>15</sup> V. Mittal,<sup>15</sup> O. T. Oayda,<sup>15</sup> D. J. Schwarz,<sup>4</sup> P. Tiwari,<sup>16</sup> T. Trombetti,<sup>5,6</sup> and J. D. Wagnveld<sup>14</sup>

- Work done by Hale, von Hausegger, Wagnveld and collaborators
- Sample  $\Lambda$ CDM matter density field with GLASS
- Source populations (i.e., AGNs and SFGs) with T-RECS
- Noise and source detectability assuming SKA-Mid (780 MHz, AA4)
- Add the signal of our motion
- ? What's the effect of faint SFGs?

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D. Bertacca,<sup>1,2,3</sup> L. Böhme,<sup>4</sup> B. Bottazzi Baldi,<sup>1,2</sup> C. Burigana,<sup>5,6</sup> M. Y. Elkhatab,<sup>7,8,9,10</sup> C. L. Hale,<sup>11,12</sup> S. von Hausegger,<sup>13</sup> H.-R. Klöckner,<sup>14</sup> M. Land-Strykowski,<sup>15</sup> G. Lewis,<sup>15</sup> V. Mittal,<sup>15</sup> O. T. Oayda,<sup>15</sup> D. J. Schwarz,<sup>4</sup> P. Tiwari,<sup>16</sup> T. Trombetti,<sup>5,6</sup> and J. D. Wagnveld<sup>14</sup>

- Work done by Hale, von Hausegger, Wagnveld and collaborators
- Sample  $\Lambda$ CDM matter density field with GLASS
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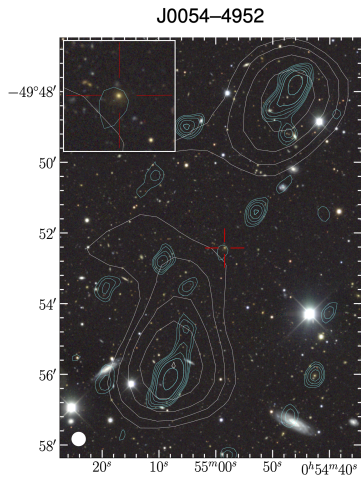
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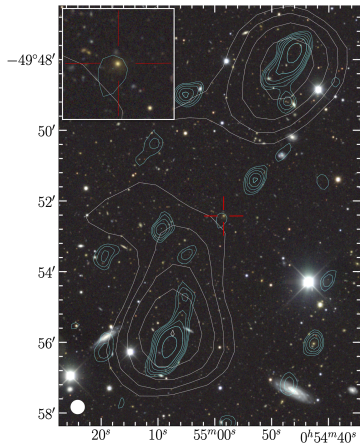
# Likelihood Function



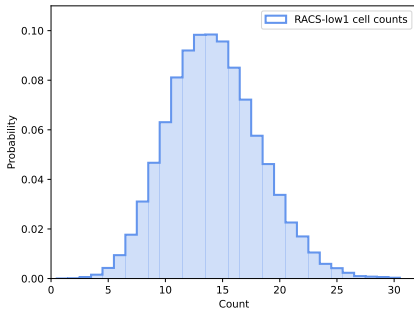
The radio sky is complex! GRSs from  
Andernach et al. (2021).

# Likelihood Function

J0054-4952

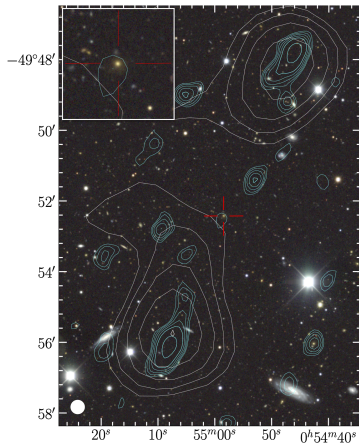


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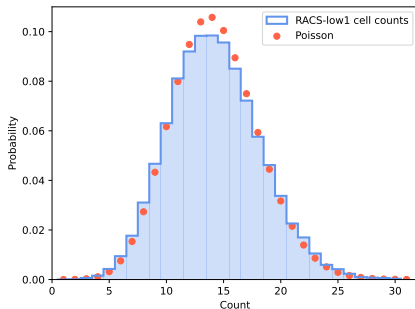
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J0054-4952



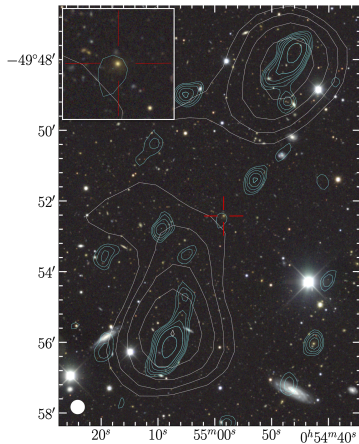
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➤ Naive assumption: sources are  
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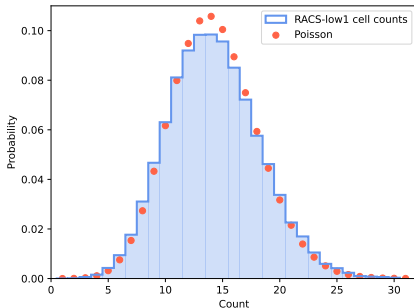
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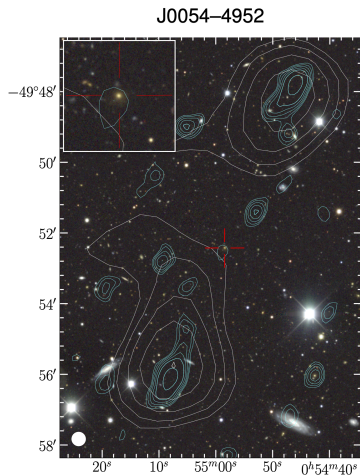


The radio sky is complex! GRSs from  
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- Naive assumption: sources are *independent*.
- But multi-component sources are *correlated*.

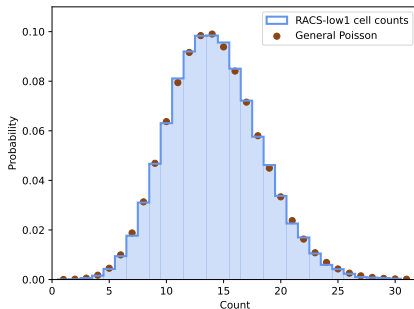


# Likelihood Function



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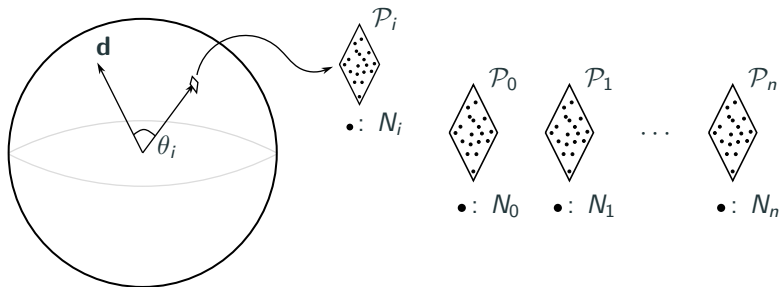
- Naive assumption: sources are *independent*.
- But multi-component sources are *correlated*.
- See e.g. von Hausegger+25 — *over-dispersed Poisson*.



## Cosmic multipoles in galaxy surveys – I. How inferences depend on source counts and masks

Oliver T. Oayda ,  Vasudev Mittal  and Geraint F. Lewis 

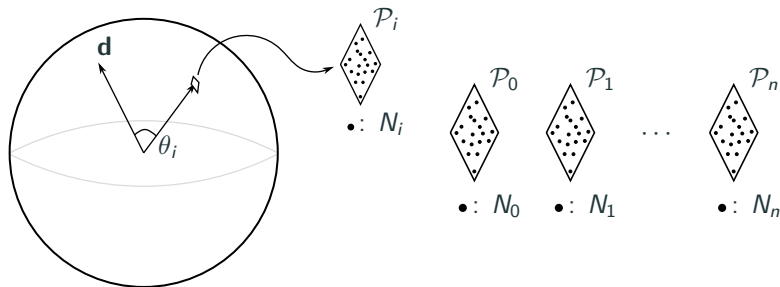
*Sydney Institute for Astronomy, School of Physics A28, The University of Sydney, NSW 2006, Australia*



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$$\mathbb{E}[N_i] = \bar{N} \left( 1 + \mathcal{D} \cos \theta_i + \sum_{j>1} f_{\ell=j} \right)$$

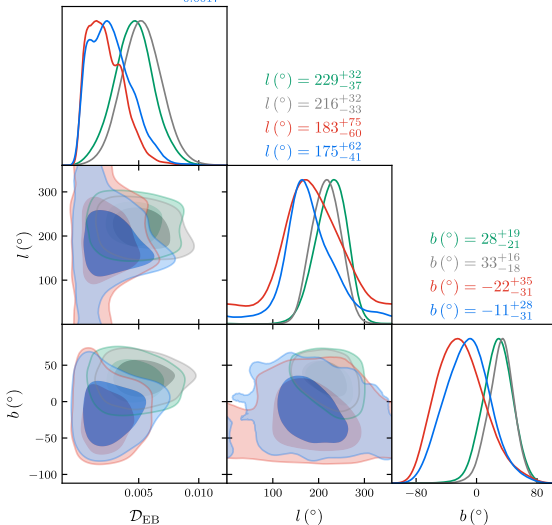
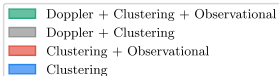
# Preliminary Results — 0.5 mJy & $z > 0.5$

$$\mathcal{D}_{\text{EB}} = 0.0046^{+0.0016}_{-0.0016}$$

$$\mathcal{D}_{\text{EB}} = 0.0052^{+0.0017}_{-0.0016}$$

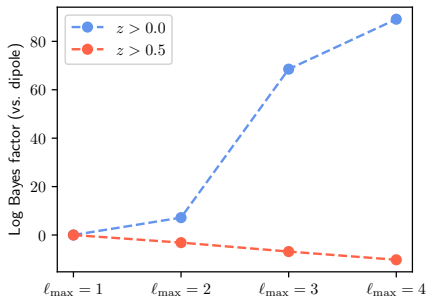
$$\mathcal{D}_{\text{EB}} = 0.0021^{+0.0017}_{-0.0013}$$

$$\mathcal{D}_{\text{EB}} = 0.0025^{+0.0020}_{-0.0017}$$



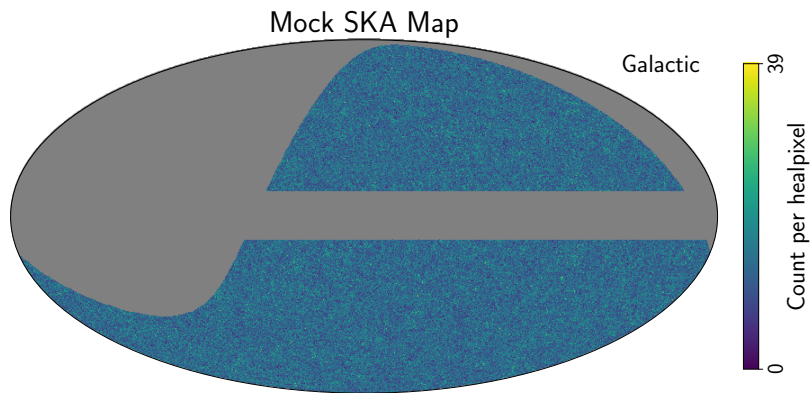
# Preliminary Results — 0.5 mJy

with M. Land-Strykowski and V. Mittal

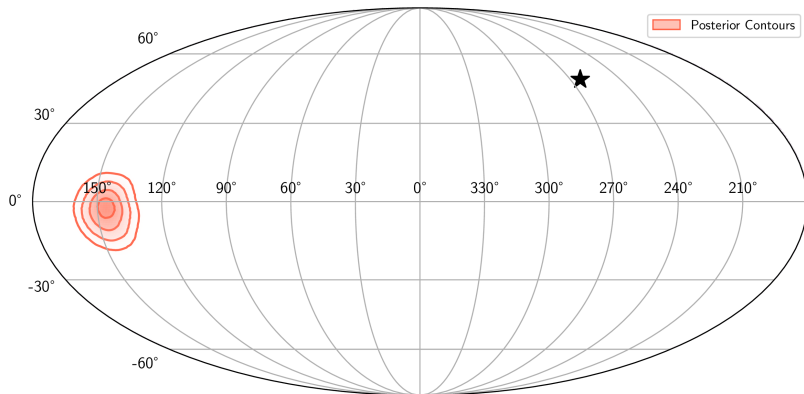


- Inference benefits with higher  $\ell$  for low  $z$
- Local clustering multipoles dominate

# Clustering Dipole

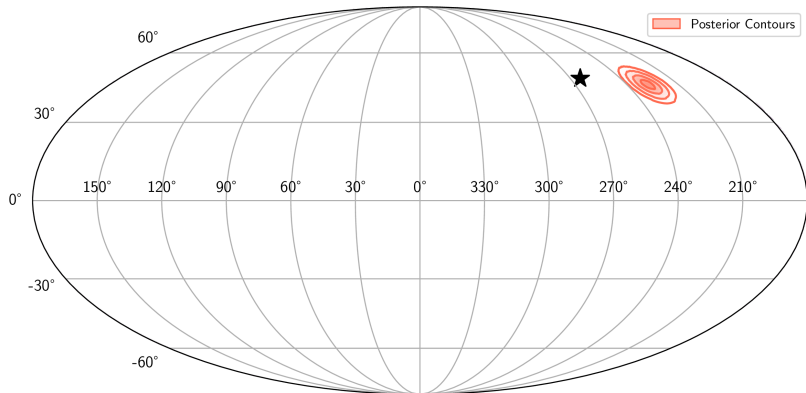


# Clustering Dipole



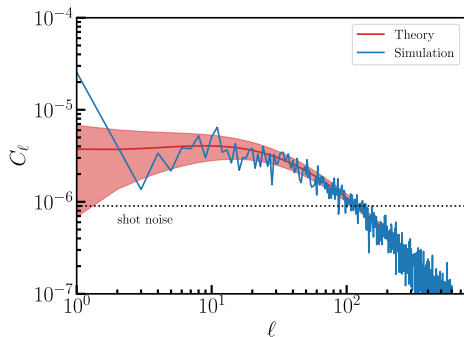
➤ Clustering dipole.

# Clustering Dipole



➤ Clustering 'drags' inferred dipole.  $D_{\text{clust.}} \approx 0.002$ ,  $D_{\text{kin.}} \approx 0.005$

# Clustering Dipole



SKA simulation matter power spectrum  
(credit: Sebastian von Hausegger)

- $\ell = 1$  moment in  $\Lambda$ CDM matter power spectrum affects dipole inference
- May need additional redshift information

➤ **Exciting new look at the cosmic dipole** ✓

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- **Bayesian pipeline with higher order multipoles** ✓

- Exciting new look at the cosmic dipole ✓
- Bayesian pipeline with higher order multipoles ✓
- How can we deal with local sources? ?